

# Surface temperatures of the Mid-Pliocene North Atlantic Ocean: implications for future climate

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The Mid-Pliocene is the most recent interval in the Earth's history to have experienced warming of the magnitude predicted for the second half of the twenty-first century and is, therefore, a possible analogue for future climate conditions. With continents basically in their current positions and atmospheric CO<sub>2</sub> similar to early twenty-first century values, the cause of Mid-Pliocene warmth remains elusive. Understanding the behaviour of the North Atlantic Ocean during the Mid-Pliocene is integral to evaluating future climate scenarios owing to its role in deep water formation and its sensitivity to climate change. Under the framework of the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) sea surface reconstruction, we synthesize Mid-Pliocene North Atlantic studies by PRISM members and others, describing each region of the North Atlantic in terms of palaeoceanography. We then relate Mid-Pliocene sea surface conditions to expectations of future warming. The results of the data and climate model comparisons suggest that the North Atlantic is more sensitive to climate change than is suggested by climate model simulations, raising the concern that estimates of future climate change are conservative.

**Keywords:** North Atlantic; Pliocene; sea surface temperature; climate sensitivity

## 1. Introduction and background

With increasing awareness and acceptance of global warming, looking back at the last interval in the Earth's history that experienced warming of the magnitude predicted for the second half of the twenty-first century becomes prudent. If one accepts a 2–3°C range of increase in global mean temperature (see Chandler *et al.* 2008) as is likely for the late twenty-first century, then the Mid-Pliocene becomes a likely analogue for future climate conditions (Hansen *et al.* 2006; Dowsett 2007; Jansen *et al.* 2007).

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Whether investigating the recent or Pliocene, or any time in between, the North Atlantic is a primary region for study owing to its role in deep water formation and its sensitivity to climate change (Keigwin *et al.* 1994). The physical ocean is an extremely complex system, incompletely understood even today. Important features of the Pliocene North Atlantic have been investigated in great detail by many workers (e.g. Sarnthein & Fenner 1988; Ruddiman *et al.* 1989; Dowsett & Poore 1991; Raymo *et al.* 1996; Dowsett *et al.* 1999). The overall pattern of the Mid-Pliocene North Atlantic surface palaeoceanography is fairly well known: an anticyclonic circulation system with a subtropical gyre; a western boundary current moving heat from the equator towards the poles; cooler return currents along the eastern margin; and regional upwelling centres, similar to the present day. The poles were cool and the tropics were warm, but relative to present day, the Mid-Pliocene meridional temperature gradient was reduced by as much as 5°C (Dowsett *et al.* 1992), and, away from centres of upwelling, low-latitude surface temperatures were indistinguishable from present-day conditions. Sea level stood higher by 25 m (see Dowsett 2007; Dwyer & Chandler 2009), and Arctic sea ice was greatly reduced (Cronin *et al.* 1993; Knies *et al.* 2002).

The goals of this paper are first to synthesize the past studies that help to understand and reconstruct the Mid-Pliocene North Atlantic region, and second to relate Mid-Pliocene conditions to future warming. We use the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) sea surface reconstruction, the only existing comprehensive reconstruction of palaeoclimatic conditions for the Mid-Pliocene, as a framework within which to better understand the Mid-Pliocene conditions in the North Atlantic region, and the Goddard Institute for Space Studies (GISS) atmospheric Global Climate–Middle Atmosphere Model (GCMAM) III to compare these conditions with future projections of global warming.

## 2. Reconstruction methods and chronology

Stratigraphic framework is fundamental to any palaeoenvironmental or palaeoclimate reconstruction. Dowsett & Robinson (2006) evaluated and modified the stratigraphic framework for the Mid-Pliocene North Atlantic used for PRISM work. Numerous faunal, magnetic and tuned isotopic events make correlation possible. Because resolution in the deep sea is limited by available sediment archives, bioturbation and the time-averaged nature of the palaeoclimate signal, the PRISM reconstruction uses a broad 300 kyr time slab that is relatively easy to recognize.

The PRISM interval was originally established as 3.15–2.85 Ma following the Berggren *et al.* (1985) time scale (Dowsett *et al.* 1994). Down-core studies of several marine microfossil groups, high-latitude vegetation data and evidence of higher-than-present sea level suggested that this was the most recent interval in which consistent and significant warmer-than-present conditions existed in the geological past (Dowsett *et al.* 1994). With the addition of the geomagnetic polarity time scale of Berggren *et al.* (1995), the astronomically tuned time scale of Lourens *et al.* (1996) and abundant data indicating warmer-than-present conditions on a global scale, the PRISM interval chronology was recalibrated to 3.29–2.97 Ma (time scale of Gradstein *et al.* 2004; figure 1).

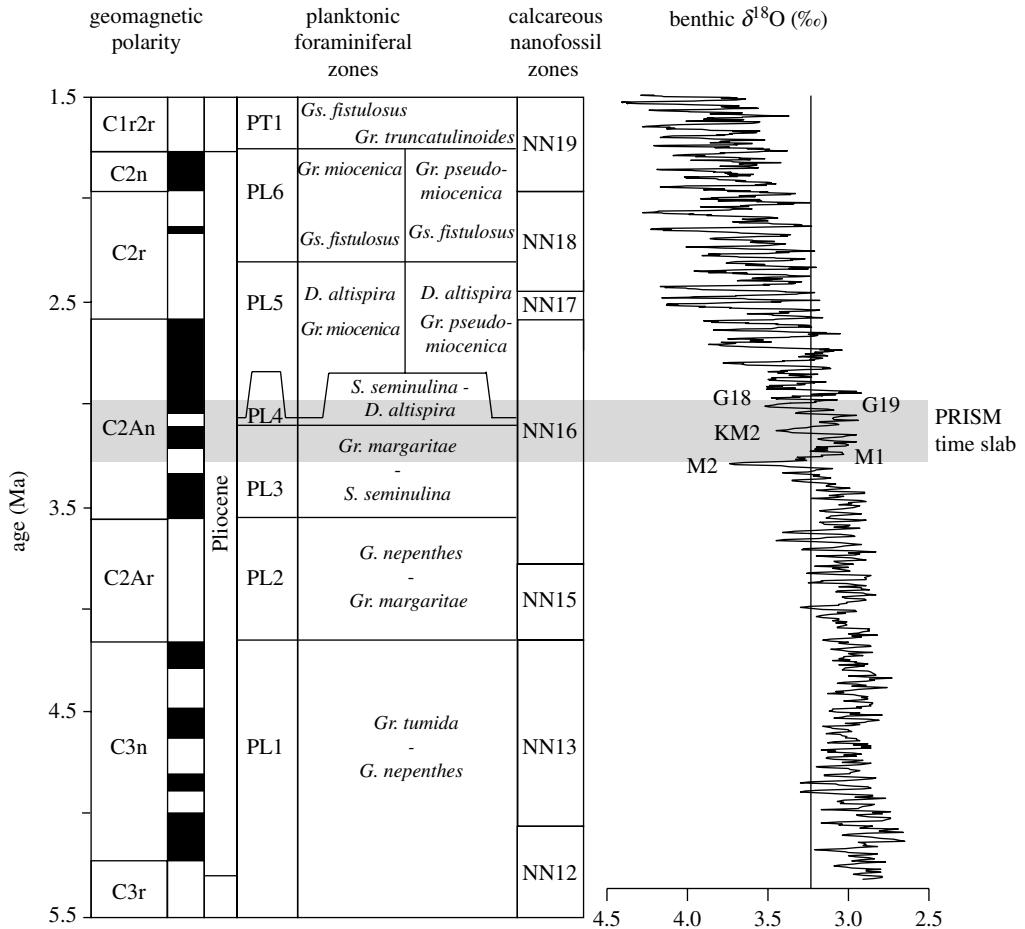


Figure 1. Pliocene magneto-biostratigraphic framework, after Berggren *et al.* (1995). The grey band approximates the PRISM time slab. The benthic  $\delta^{18}\text{O}$  record is from Lisiecki & Raymo (2005).

The PRISM interval is a period of relatively warm, yet variable, climate between the transition of marine oxygen isotope stages M2/M1 and G19/G18 (Shackleton *et al.* 1995) in the middle part of the Gauss Normal Polarity Chron (C2An) and ranges from within C2An2r (Mammoth reversed polarity) to near the bottom of C2An1 (just above Kaena reversed polarity). This interval correlates in part to planktonic foraminiferal zones PL3 (*Globorotalia margaritae*–*Sphaeroidinellopsis seminulina* Interval Zone), PL4 (*S. seminulina*–*Dentoglobigerina altispira* Interval Zone) and PL5 (*D. altispira*–*Globorotalia miocenica* Interval Zone) of Berggren *et al.* (1995). It falls within the calcareous nanofossil zone NN16 of Martini (1971) or CN12a of Bukry (1973, 1975); see Dowsett & Robinson (2006). In the remainder of this paper, the PRISM interval and PRISM time slab are used synonymously.

Three primary methods of sea surface temperature (SST) estimation are used for the PRISM interval in the North Atlantic: faunal-based transfer functions; Mg/Ca palaeothermometry; and the alkenone  $U_{37}^{K'}$  index. The PRISM factor

analytic transfer function used for the North Atlantic sequences (GSF18) has been described previously (Dowsett & Poore 1990; Dowsett 1991, 2007). For shallow marine sequences, an ostracode transfer function was developed (Cronin & Dowsett 1990). These two equations have been used for most of the faunal-based temperature estimates discussed below and have associated errors of  $\pm 1.5^{\circ}\text{C}$  and  $\pm 1.8^{\circ}\text{C}$ , respectively.

Mg/Ca methodology is based upon the observed increase in Mg/Ca in biogenic calcite with increasing temperature (Dwyer *et al.* 1995; Nürnberg 1995; Nürnberg *et al.* 1996; Rosenthal *et al.* 1997, 2000; Lea *et al.* 1999; Elderfield & Ganssen 2000; Anand *et al.* 2003). A summary of the technique can be found in Lear (2007). For the PRISM interval in the North Atlantic region, several workers (Groeneveld 2005; Bartoli *et al.* 2006; Robinson *et al.* 2008) have applied the Mg/Ca technique as discussed below. Error on Mg/Ca palaeothermometry has been estimated at  $\pm 1.2^{\circ}\text{C}$  by Dekens *et al.* (2002).

Alkenone palaeothermometry (or the calibrated  $U_{37}^{K'}$  index) is summarized by Volkman (2000), Herbert (2001, 2004) and Lawrence *et al.* (2007). The method is based upon the temperature dependence of the double and triple carbon bonds in the alkenones produced by haptophyte algae. Herbert & Schuffert (1998) and Robinson *et al.* (2008) have applied the alkenone method within the PRISM interval in the North Atlantic region. Estimates derived using this technique have an error of  $\pm 1.3^{\circ}\text{C}$  (Lawrence *et al.* 2007).

### 3. Descriptive regional palaeoceanography

Sections 3a–3g briefly summarize the important regions of the Mid-Pliocene North Atlantic (as indicated by corresponding letters A–G on figure 2a), using the existing PRISM2 reconstruction as a framework. Site locations are shown in figure 2b.

#### (a) Caribbean Sea

One cannot discuss the regional conditions within the Caribbean without making reference to the status of the Central American Isthmus (CAI) and the Central American Seaway (CAS). During the Mid- to Late Miocene, the CAS was open, and both deep and surface waters were exchanged between the Caribbean and the eastern equatorial Pacific (EEP). Owing to subduction of the Cocos and Nazca plates under the North and South American and later Caribbean plates, the CAI gradually rose and first impeded deep water and finally surface water exchange with the Pacific. By 4.6–4.2 Ma, the CAS had shoaled to less than 100 m depth (Haug & Tiedemann 1998). Once the CAS was completely closed, a greater amount of surface water, and the heat contained within, was diverted north along the coast of North America, creating the Gulf Stream Current. The Gulf Stream becomes the North Atlantic Drift that today ameliorates the climates of northwestern Europe (Tomczac & Godfrey 1994).

Despite being effectively closed by the PRISM interval, the CAS was breached repeatedly possibly as late as 2.4 Ma (Stehli & Webb 1985; Cronin & Dowsett 1996; Webb 1997; Kameo & Sato 2000; Groeneveld *et al.* 2006; Steph *et al.* 2006; Schmidt 2007; Williams *et al.* 2009).

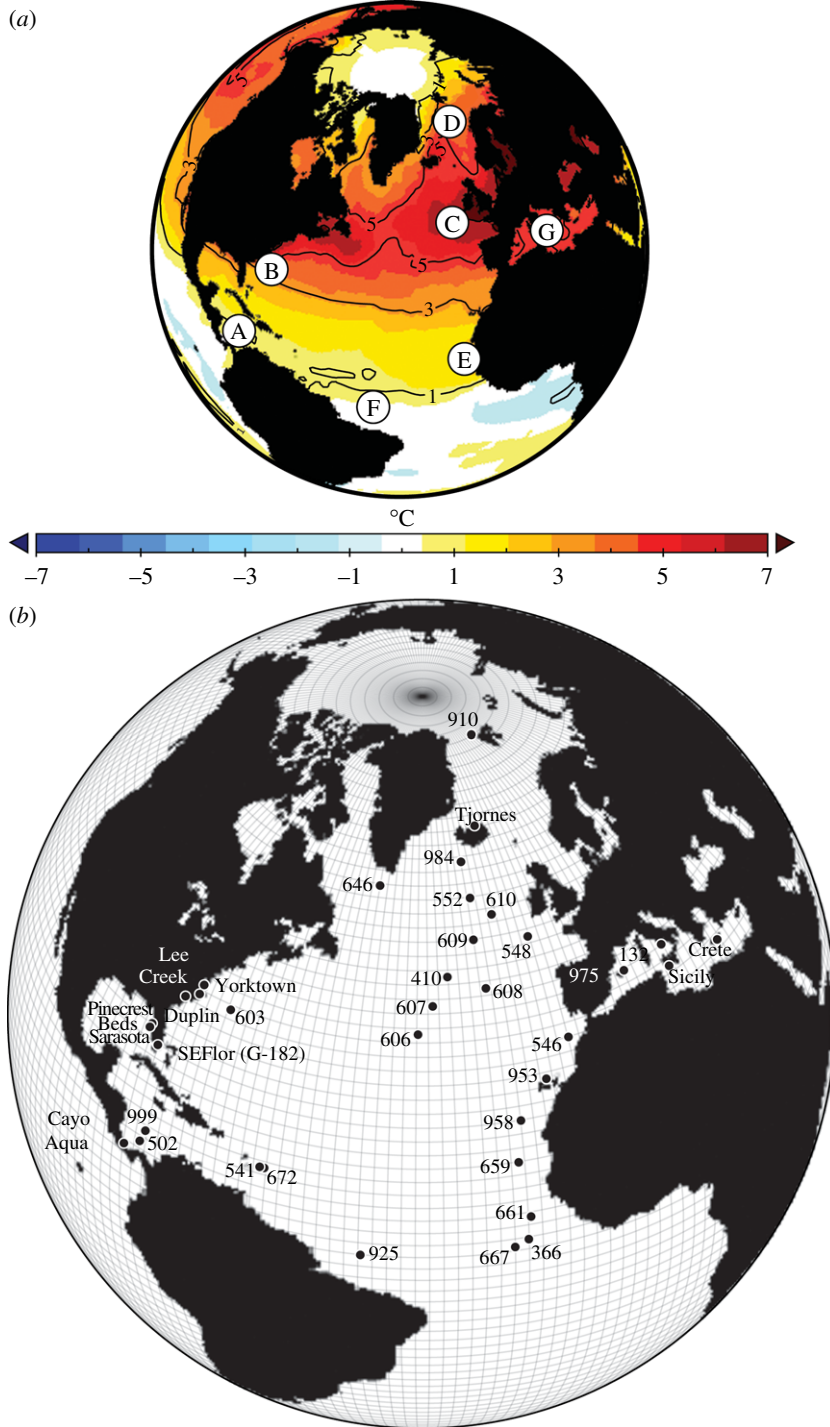


Figure 2. (a) Mean annual SST anomaly for the North Atlantic region as estimated by the PRISM2 dataset (letters A–G correspond to §3a–g respectively). (b) Localities discussed in the text.

The PRISM reconstruction includes five sites in the Caribbean Sea (*figure 2b*). The planktonic foraminiferal faunas of Site 502 are well preserved and show remarkable similarity to the present-day assemblages, and hence to modern conditions (Dowsett & Poore 1991; Dowsett & Robinson 2007). The SST anomaly developed from Site 502, and assemblages recovered from Cayo Agua (Cronin & Dowsett 1996), suggest that conditions in the Caribbean during the PRISM interval were 28–29°C, within 1°C of the present-day conditions. Sites 541 and 672, technically just east of the Caribbean Sea yet still within 15° of the Equator, also show SST anomalies of less than 1°C relative to the present-day conditions (Dowsett & Robinson 2006).

At Site 999, Mg/Ca palaeothermometry provides a mean annual SST within 1°C of modern mean annual SST (Groeneveld 2005). Thus, faunal-based estimates from Sites 502, 541 and 672 and the Mg/Ca-based estimates from Site 999 corroborate conditions similar to those of today in the Caribbean region during the Mid-Pliocene.

### (b) *Gulf Stream*

Shallow marine sites in south Florida (Sarasota, Pinecrest Beds and SEFlor G-182), similar to the Caribbean sites discussed above, show no evidence of warming. In fact, these locations show slight (less than 1°C) cooling with respect to the present-day mean annual conditions based upon quantitative analyses of ostracode faunas (Cronin 1991; Willard *et al.* 1993).

Further north, along the east coast of North America, open ocean Site 603 (Dowsett & Poore 1991) and Duplin and Yorktown land sections (Cronin 1991; Dowsett & Wiggs 1992) show warmer-than-present conditions, and these anomalies appear to increase with latitude (*figure 2a*). The Raysor and Duplin Formations and Yorktown Formation (at Lee Creek and in its type locality near the Virginia/North Carolina border) and Site 603 also share another feature: decreased seasonality. Winter season temperatures at Lee Creek are approximately 2°C warmer than present day but 5°C warmer to the north at Yorktown and offshore at Site 603. Summer season temperatures at these locations change by less than 2°C. Thus, warming of the Gulf Stream appears to have been accomplished by warmer winter season temperatures (see also Williams *et al.* 2009).

### (c) *North Atlantic Drift/northeast Atlantic*

On and east of the mid-Atlantic Ridge, a transect of cores, beginning with Site 606 in the south and ending with Site 552 in the north, allows an estimate of the breadth and magnitude of warming associated with the northern limb of the North Atlantic gyre (*figure 2*). Site 606 shows a small degree of warming (1–2°C) and is today situated just south of the North Atlantic Current in the central gyre. Clear warming is documented by displacement of planktonic foraminiferal assemblages to the north, relative to present day. Warming increases northwards along the transect. At Site 552, the mean annual temperature anomaly is greater than or equal to 5°C (Dowsett & Poore 1990, 1991; Dowsett & Robinson 2007) based upon quantitative analyses of planktonic foraminiferal assemblages and is corroborated by Mg/Ca and alkenone palaeotemperatures (Robinson *et al.* 2008).



Few sites offer direct observations of the North Atlantic Drift, west of the mid-Atlantic Ridge (figure 2b). Cool temperatures at Site 646, however, define the western boundary of the warm northern limb of the North Atlantic gyre (Dowsett & Poore 1991).

(d) *Sub-polar North Atlantic*

To the north of these northeast Atlantic sites, warming relative to the present-day conditions has been documented at Site 984, Tjornes, Iceland, and Site 910. The data from Site 984 (approx. 2°C warming with respect to modern temperature) come from Mg/Ca estimates (Bartoli *et al.* 2006); those from Tjornes, Iceland (Cronin 1991) and Site 910 (Cronin & Whatley 1996) are based upon quantitative and qualitative analysis of the ostracode fauna, respectively. Estimates of warming at Tjornes are approximately 5°C above modern mean annual temperature. According to Cronin & Whatley (1996), warm Atlantic water entered the Yermak Plateau region during parts of the Pliocene, as evidenced by temperate species inhabiting 500–1000 m water depths.

Our own in-progress multiproxy work suggests that Mid-Pliocene warmth extended well into the Arctic Ocean (at least to 80° N), in agreement with previous faunal, floral and sedimentological data (Cronin & Whatley 1996; Willard 1996; Knies *et al.* 2002). The warm conditions at these latitudes suggest a significant transfer of heat northwards from the low latitudes to the polar region.

(e) *Eastern Boundary Current*

Today, the cool southward-flowing Canary Current (part of the Eastern Boundary Current of the North Atlantic gyre) exhibits a mean annual SST of approximately 20.2°C in the Canary Island region. At Site 953, the planktonic foraminiferal assemblage from the Mid-Pliocene records an anomalous pulse of warm subtropical conditions (Brunner & Maniscalco 1998). Just north of the Canaries and due west of Casablanca at Site 546, the SST was approximately 2°C warmer than the present-day conditions (Dowsett 2007). These results suggest that warmer Mid-Pliocene waters in the northeast Atlantic led to a warmer Eastern Boundary Current and that the warm anomaly diminished with decreasing latitude.

Further south at Site 958, Herbert & Schuffert (1998) show mean annual temperatures approximately 3°C warmer than present day. Site 958 is located well west of coastal upwelling and, therefore, is taken as a true monitor of oceanic conditions, not subject to regional intensification of the upwelling system off northwest Africa (Pflaumann *et al.* 1998). Sites 958, 659, 661, 667 and 366 form a transect outside the regional upwelling zone off northwest Africa, north of the equatorial divergence, covering 20° of latitude. This transect shows progressively less warming relative to today as one moves closer to the Equator (Dowsett *et al.* 1999; Dowsett & Robinson 2006, 2007; Dowsett 2007).

(f) *Equatorial Atlantic*

Few equatorial Atlantic sites with well-preserved and abundant Mid-Pliocene planktonic foraminiferal assemblages have been investigated in detail. Semi-quantitative analysis of the foraminiferal faunas at Site 925

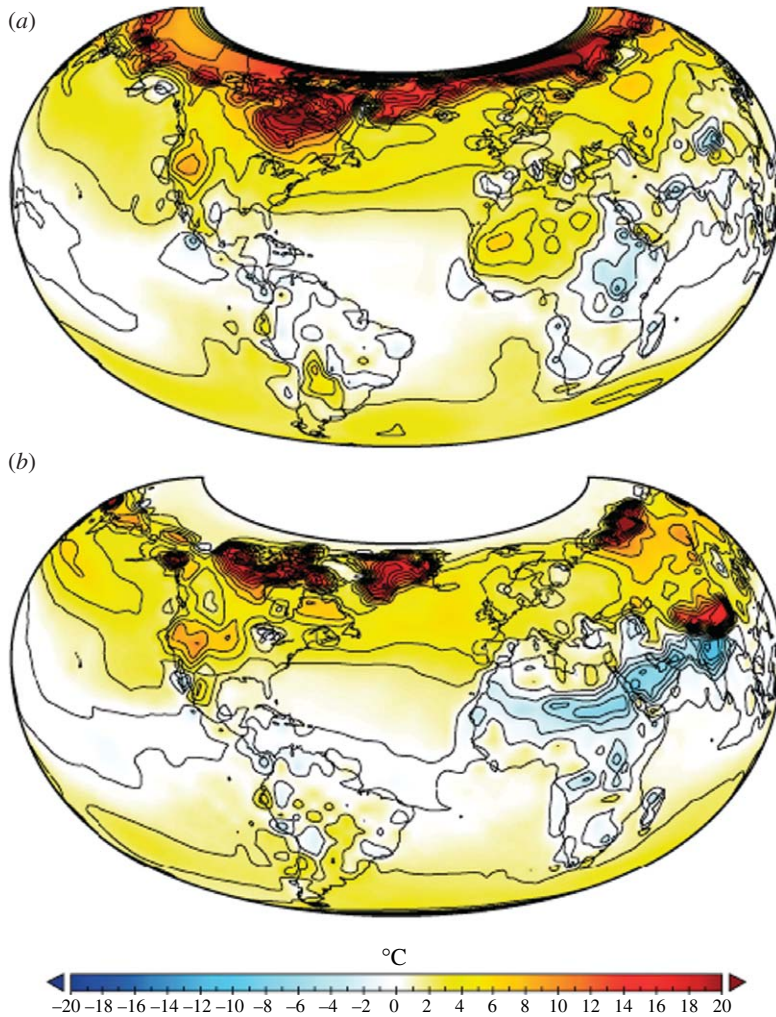


Figure 3. Surface air temperature anomalies as simulated by the NASA/GISS atmospheric GCMAM III. The values are (a) winter (December–February) and (b) summer (June–August) averages from the final 10 years of both Pliocene and modern climate 20-year integrations. Surface air temperature in the GISS GCMAM is calculated at a height of 2 m above the surface.

(Chaisson & Pearson 1997) reveals an assemblage remarkably similar to the present-day faunas in the region, suggesting warm tropical SSTs at this site not unlike modern conditions.

#### (g) *Mediterranean Sea*

The Mediterranean region has been studied intensely for many years, and quantitative planktonic foraminiferal data are plentiful (e.g. Thunell 1979*a,b*; Spaak 1983; Zachariasse *et al.* 1990; Serrano *et al.* 1999; Sprovieri *et al.* 2006).

At Site 132 in the central Mediterranean, Thunell (1979*a,b*) estimated temperatures for the Mid-Pliocene to be 1–2°C warmer than present day. This is generally in agreement with the later work at Site 975 (Serrano *et al.* 1999) that



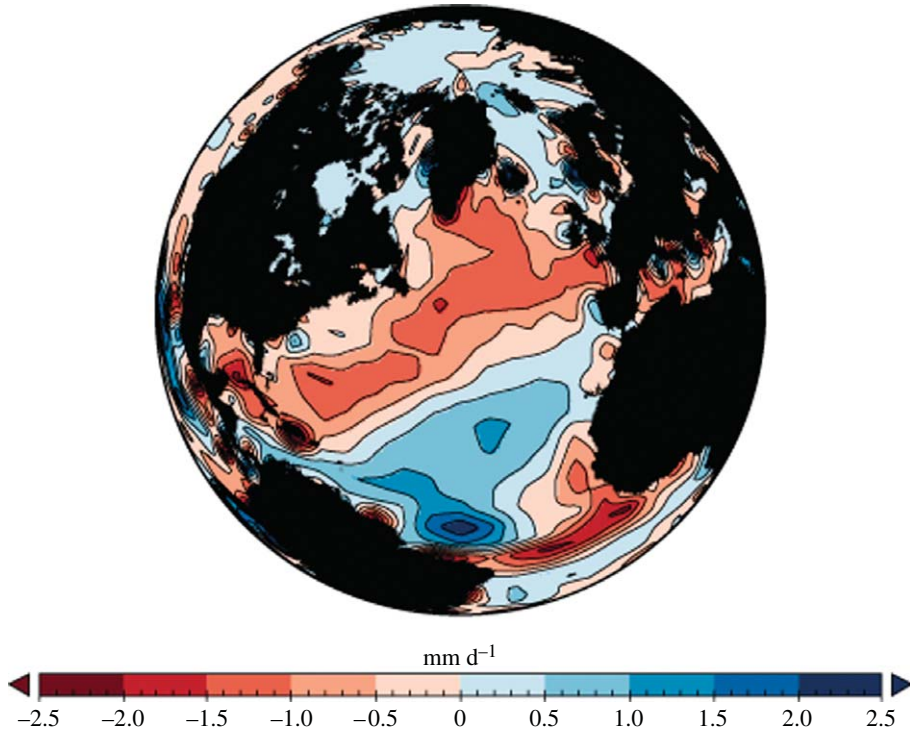


Figure 4. Based on atmospheric GCM experiments, the moisture balance over the North Atlantic in the Pliocene was more negative than today, suggesting that surface salinity may have been higher, driving increased deep water production.

shows conditions similar to present day punctuated several times by subtropical and therefore warmer assemblages. Marine sequences analysed by [Spaak \(1983\)](#) from the islands of Sicily and Crete reveal similar SST conditions, although somewhat reduced seasonality (slightly cooler summer conditions) relative to present day. From the same region, [Zachariasse \*et al.\* \(1990\)](#) show peak warming to have been approximately 2°C warmer than at present.

#### 4. Relationship to future climate

The Mid-Pliocene is the most recent global warming in the Earth's history to have approached the level of temperature increase that the Intergovernmental Panel on Climate Change (IPCC) projects for the latter part of this century. Global Mid-Pliocene peak warmth of 2–3°C above current global temperatures places the Mid-Pliocene squarely in the range of climate model projections for the latter part of the twenty-first century, even assuming emission rates that are somewhat less than those we are experiencing in this decade. [Figure 3](#) shows the surface air temperature anomalies produced by the NASA/GISS atmospheric GCMAM III ([Rind \*et al.\* 2007](#)) when forced by PRISM2 surface conditions. Over the ocean, most of the change in temperature is a result of the specified SST forcing, and the warm North Atlantic in the Gulf Stream region is apparent, particularly in summer.

Further north, over the Arctic, most of the warming is related to the decreased Pliocene sea ice in the PRISM2 dataset, an effect that is dominant in the winter months. This high-latitude temperature amplification, especially in the Arctic Ocean, is certainly considered a hallmark of global warming forecasts; thus, the Mid-Pliocene SST increase and sea ice decrease in the Arctic might be considered analogous to a mature warm climate state. The rapid melting of Arctic sea ice in recent years, particularly during the summer of 2007 and, despite a cold intervening winter, again in the summer of 2008, may indicate that the region is progressing towards a Pliocene-like state at a more rapid pace than even the most sensitive climate models have predicted.

The story in the North Atlantic could be even more disconcerting if Mid-Pliocene climate is indeed illustrative of a mature warm climate state. In almost all coupled climate models, meridional overturning circulation (MOC) in the North Atlantic Ocean slows as global warming proceeds. This reduction in the MOC in the mid- to high-latitude North Atlantic results in decreased ocean heat transport into the region, reducing (if not temporarily reversing) warming due to radiative effects. Consistent with this response, Mid-Pliocene simulations using coupled general circulation models (GCM), forced by Pliocene palaeogeographic land surface conditions, find that the production of deep water in the North Atlantic declines. Simulations using a version of the NASA/GISS coupled ocean–atmosphere models show a decrease of approximately 5 sverdrups ( $5 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ ; approx. 15%) at the peak overturning compared with modern climate control runs (see Hansen *et al.* (1997) for a detailed description of the atmospheric model and ‘Ocean C’ version of the coupled dynamic ocean GCM). In complete contrast, the PRISM SST records show the greatest warming in this region. The role of the MOC in the Mid-Pliocene warming is supported by independent analyses, suggesting that the North Atlantic deep water production increased during the PRISM interval (Raymo *et al.* 1996; Billups *et al.* 1997).

Although the coupled climate model simulations forced by increasing greenhouse gas emissions or by Pliocene land surface conditions do not show an increase in North Atlantic deep water production, there is some indication from model sensitivity experiments (Stouffer & Manabe 2003) that the decreases seen in the IPCC model simulations may not be permanent, and that longer integrations could show an MOC in the Pliocene, or other warm climate simulations, that recovers to modern values in time. In addition, we have conducted atmosphere-only GCM experiments, forced by PRISM SSTs, which show changes in the moisture balance over the North Atlantic that could support increased salinity, thus increased density of surface waters in the region (figure 4). While coupled models should provide a predictive capacity to examine the effect, they do not reproduce the strong PRISM North Atlantic SST anomaly that may ultimately indicate an inability to generate the appropriate hydrological atmospheric feedbacks (cloud cover, storm track changes, precipitation and evaporation) to initiate the altered MOC.

An additional question exists over warming in low latitudes during the Mid-Pliocene. Figure 2a shows that PRISM2 SST anomalies throughout the low-latitude Atlantic were within  $1^\circ\text{C}$  of the present-day conditions. These anomalies were developed from discrete data at Sites 366, 502, 541, 661, 667, 672 and Cayo Aqua. Warming at all latitudes would be an indication of greenhouse-type warming and would suggest elevated greenhouse gases. Mid-Pliocene proxy

data in the tropics, however, outside of the regions of upwelling, show little warming of the sea surface, a pattern that is not consistent with future global climate model projections of tropical climate change forced by increased CO<sub>2</sub>.

These discrepancies raise serious questions about the applicability of the proxies, the sensitivity of climate models in the North Atlantic to greenhouse gas increases, and the validity of the analogy between the mature (Mid-Pliocene) and transient (late twenty-first century) climate states. Ideally, the continuation of palaeoclimate studies of the Mid-Pliocene and the improvement of models will lead to the answers to these questions.

## 5. Summary

Knowledge of Mid-Pliocene palaeoceanography was gained through an immense volume of geochemical, faunal and floral analyses acquired by many workers at varying resolution and from different regions. In the last few years, the latest generation of coupled ocean–atmosphere climate models have demanded more detailed information about the state of the Pliocene ocean and regional to sub-regional characteristics. In response to this greater demand, researchers have used innovative tools, developed new proxies for different oceanic variables and re-analysed existing data. We have reviewed and synthesized the large volume of data that exist for the Mid-Pliocene North Atlantic Ocean for a narrowly focused stratigraphic interval (3.3–3.0 Ma) and have related the resulting conceptual SST reconstruction to future warming.

Mid-Pliocene SST was estimated for seven regions of the North Atlantic using faunal-based transfer functions, Mg/Ca palaeothermometry and the alkenone  $U_{37}^{K'}$  index. Mid-Pliocene conditions were similar to those of today in the equatorial Atlantic, the Caribbean and southern Florida, but the Gulf Stream was warmer than present owing to warmer winter season temperatures. Along the North Atlantic Drift, warming increased northwards from 1–2°C to 5°C or more, and this warming increased in the sub-polar North Atlantic and Arctic Oceans, suggesting a significant transfer of heat northwards from the low latitudes to the polar region. Warmer Mid-Pliocene waters in the northeast Atlantic led to a warmer Eastern Boundary Current, with warming that decreased towards the Equator. In the Mediterranean, SST was at most 2°C warmer than present, with somewhat reduced seasonality.

Coupled climate models do not reproduce the strong northeast North Atlantic SST anomaly indicated by the data, and tropical data, outside of upwelling regions, do not show warming consistent with future global climate model projections forced by increased CO<sub>2</sub>. Unresolved discrepancies between the data and modelling studies suggest climate sensitivities in excess of what would be expected, given the estimated levels of greenhouse gas increases, raising the concern that model estimates of future climate change may be conservative.

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